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21st CENTURY EXTRAVEHICULAR ACTIVITIES: SYNERGIZING PAST AND PRESENT TRAINING METHODS FOR FUTURE SPACEWALKING SUCCESS

Sandra K. Moore, Ph.D.
United Space Alliance, LLC
600 Gemini, Houston TX, 77058-2783 ; USA
sandra.k.moore@nasa.gov

Matthew A. Gast
United Space Alliance, LLC
600 Gemini, Houston TX, 77058-2783; USA
matthew.gast-1@nasa.gov

Abstract

Neil Armstrong's understated words, "That's one small step for man, one giant leap for mankind." were spoken from Tranquility Base forty years ago. Even today, those words resonate in the ears of millions, including many who had yet to be born when man first landed on the surface of the moon. By their very nature, and in the true spirit of exploration, extravehicular activities (EVAs) have generated much excitement throughout the history of manned spaceflight. From Ed White's first space walk in June of 1965, to the first steps on the moon in 1969, to the expected completion of the International Space Station (ISS), the ability to exist, live and work in the vacuum of space has stood as a beacon of what is possible. It was NASA's first spacewalk that taught engineers on the ground the valuable lesson that successful spacewalking requires a unique set of learned skills. That lesson sparked extensive efforts to develop and define the training requirements necessary to ensure success. As focus shifted from orbital activities to lunar surface activities, the required skill-set and subsequently the training methods, changed. The requirements duly changed again when NASA left the moon for the last time in 1972 and have continued to evolve through the SkyLab, Space Shuttle, and ISS eras. Yet because the visits to the moon were so long ago, NASA's expertise in the realm of extra-terrestrial EVAs has diminished. As manned spaceflight again shifts its focus beyond low earth orbit, EVA success will depend on the ability to synergize the knowledge gained over 40+ years of spacewalking to create a training method that allows a single crewmember to perform equally well, whether performing an EVA on the surface of the Moon, while in the vacuum of space, or heading for a rendezvous with Mars. This paper reviews NASA's past and present EVA training methods and extrapolates techniques from both to construct the basis for future EVA astronaut training..

Introduction

One of the most exhilarating exercises conducted during a space flight occurs when a human leaves the protective environment of his or her pressurized spacecraft to work in the hostile vacuum of space. Extravehicular activities (EVAs), or spacewalks, are a proven capability for meeting mission objectives, be they lunar sample collection or the construction of the International Space Station. Additionally, EVAs are an essential element to the future human space programs. Successful EVAs demand an array of complex technical skills, the use of advanced technologies, and an acute ability to adapt to changing requirements As space-faring nations race to return to the lunar surface, and future human space endeavors will take mankind beyond, to Mars and other extra-terrestrial destinations, great care must be taken in planning EVAs and in the training of the crews. An ever-increasing EVA capability has been developed over time, by progressively combining lessons learned from previous missions with current state-of-the-art technology. As focus shifts outside low earth orbit, the EVA operations community must become reacquainted with past training philosophies, to cull the lessons learned that will be critical to achieve future success and ensure crew safety. This paper highlights the evolution and lessons learned from NASA's EVA Task training programs within the overall mission objectives of Gemini, Apollo, Skylab, Shuttle, and the ISS, and extrapolates effective techniques to construct a basis for future EVA astronaut training.

Philosophy on EVA Training

Formal EVA training for the International Space Station and the space shuttle today is conducted by the National Aeronautics and Space Administration (NASA) Mission Operations Directorate (MOD) EVA branch. This branch is responsible for the instruction, planning, and execution of any and all activities associated with spacewalks. Current EVA training is divided into two major categories: EVA Systems and EVA Tasks. EVA Systems responsibilities consist of the extravehicular mobility unit (EMU), or spacesuit, airlock operations, and the service and maintenance equipment for this hardware. EVA Task training is comprised of generic and flight-specific training on the spacewalking activities crewmembers will be performing on orbit, as well as comprehensive training on the tools and hardware that are utilized during EVAs.

The Gemini Program (1965-1966) Beginner's Luck and the Dangers of EVA

The Gemini Project was designed to bridge the gap of understanding between the Mercury and Apollo programs in critical situations including precision guidance, navigation, re-entry, and extravehicular activity. The fortunate decision to equip Gemini spacecraft with hinged, full-opening ejection hatches unlocked the door to U.S. EVA capability (Wilde et. al. 2002).

The first planned EVA called for a crewmember to open the spacecraft hatch and "simply stand up" with his shoulders exposed outside the hatch perimeter. In November of 1964, Young & Grissom demonstrated the concept in a simulated altitude chamber at 150,000 ft wearing a prototype EVA pressurized suit (G3C). The test was a success, despite a bit of trouble encountered while attempting to close the hatch. This accomplishment allowed for serious planning of the first U.S. EVA on Gemini 4 (Shayler, 2001).

One month earlier, Commander Jim McDivitt and Pilot Ed White began evaluating initial EVA suit concepts in preparation for EVA hatch "ingress" training using a Gemini mockup in a low gravity airplane, NASA's KC-135 (Wilde et. al. 2002). The parabolic flight of the aircraft was employed to achieve 27-30 second intervals of microgravity. With practice, the Gemini-Titan III and IV crews became adept at entering the spacecraft and closing the hatch in a timely manner, wearing a spacesuit and chest pack under these microgravity conditions (Weekly Activity Report, Jan. 10-16, 1965, p. 1; Consolidated Activity Report, January 1965, pp. 12, 16.). By December, the crew began evaluating the first EVA suit prototype (G4C) for mobility in low gravity KC-135 tests. Surprisingly, the crew found that the suit was too heavy and impeded movement. Engineers were able to remove excess bulk and the crew deemed the suit satisfactory for EVA use in February (Wilde et. al. 2002).

Altitude chamber tests of the Gemini spacecraft IV began in late March of 1965, involving five simulated flights at McDonnell. The first run was unmanned. In the second run, the prime crew flew a simulated mission, but the chamber was not evacuated. The third run repeated the second with the backup crew replacing the prime crew. The fourth run put the prime crew through a flight at simulated altitude and the fifth did the same for the backup crew. Altitude chamber testing ended March 25 and the spacecraft was prepared for shipment to Cape Kennedy (Mission Report for GT-IV, p. 12-22; Weekly Activity Report, Mar. 21-27, 1965, p. 1)

The first stand-up EVA was originally planned for December of 1965; however, the US EVA community was spurred to speed up their timetable after it was learned that Russian cosmonaut Alexi Leonov performed the first EVA on March 18, 1965. Two weeks later, the possibility of doing more than the previously planned stand-up form of extravehicular activity was introduced at an informal meeting in the office of Director Robert R. Gilruth at Manned Spacecraft Center (MSC), now the NASA Johnson Space Center (JSC). Engineers ensured the director that the new EVA equipment would be ready in time for the upcoming June launch. When the news reached Washington regarding the hardware's flight-readiness, it quickly prompted Headquarters final approval.

EVA task training continued for crewmember Ed White, and included practicing the "stand-up EVA" in the altitude chambers, as well as training with a Hand-Held Self-Maneuvering Unit (Figure 1) on an air bearing floor (Figure 2) and aboard the KC-135 low gravity aircraft.

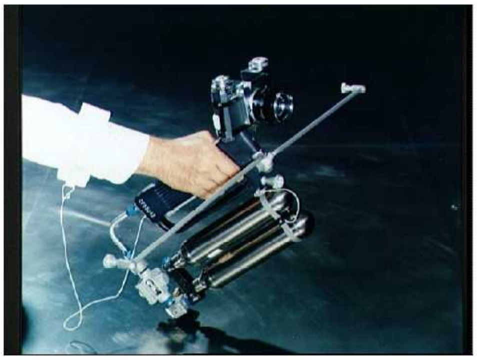

Figure 1. Hand-Held Self-Maneuvering Unit to be used during extravehicular activity (EVA) on Gemini 4 flight on the front of the unit. Photo from JSC Digital Image Collection, PHOTO ID S65-27331, taken 06-02-1965.

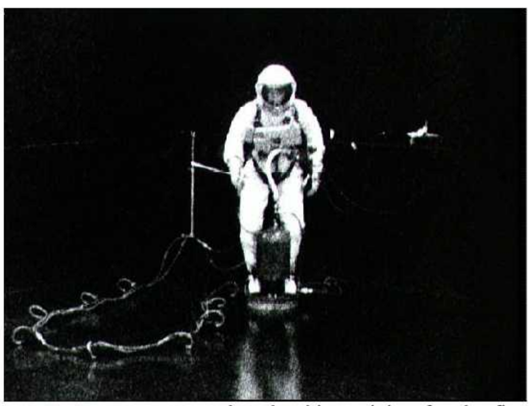

Figure 2. Astronaut Edward White training for the first EVA in bldg 4 of the Manned Spacecraft Center on the air bearing floor. Photo from JSC Digital Image Collection, PHOTO ID S65-19501, taken 03-29-1965.

NASA's foray into the world of EVA finally commenced when Ed White ventured out of the Gemini IV capsule on June 3, 1965 and "floated" at the end of a 25 foot golden umbilical for approximately 22 minutes. Although the term "spacewalk" was coined for the Gemini EVA program, no actual walking took place. The endeavor proved successful when White effectively demonstrated a small handheld jet called the Hand Held Maneuvering Unit (HHMU), which he used to propel himself through space. Figure 3 is an image of Astronaut Edward H. White II, pilot for the Gemini-Titan IV space flight, floating in the vacuum of space.

Figure 3. Astronaut Edward White during first EVA performed during Gemini 4 flight www.starshipmodeler.com/real/ed_white_eva.jpg

White's success thrust NASA onto an even playing field with Russia and paved the way for eight additional Gemini EVAs. They did not, however, all go as smoothly as the first, and NASA quickly discovered that White's success was just beginner's luck.

The second U.S. EVA was conducted by crewmember Eugene Cernan on Gemini XIII. Due to the success and ease of White's EVA, Cernan's EVA task training flow was comparable. Figure 4 shows Astronaut Eugene A. Cernan during tests with the Astronaut Maneuvering Unit (AMU) conducted in Chamber B, Environmental Test Laboratory, Building 32 of the Manned Spacecraft Center in Houston, while Figure 5 illustrates Cernan donning the Astronaut Maneuvering Unit (AMU) back pack after egressing a Gemini mock-up under microgravity conditions aboard the KC-135.

The unrealized but inherent difficulties and dangers of performing an extravehicular activity was first experienced during just the second U.S. EVA mission as Eugene Cernan demonstrated the use of a jet-propelled backpack on Gemini IX-A (June 6, 1966). Instead of using the HHMU that White had used to control and maintain his body position, Cernan evaluated the use of handrails, Velcro patches, and loop foot restraints. Cernan found these crew aids inadequate for controlling his body position. As he flailed, he broke off an experimental antenna on the Gemini IX spacecraft and tore the outer layer of his suit. Furthermore, Cernan's physical exertion increased his metabolic rate such that the resulting moisture overwhelmed the capabilities of his AMU, causing his helmet visor to fog over, effectively blinding him. At this point the EVA was terminated. Upon returning to Earth, Cernan repeated the EVA in the Water Immersion Facility (WIF), a pool 4m (16 ft) deep, by 8.5 m (28 ft) in diameter, housed at the Johnson Space Center (JSC). He reported that the neutral buoyancy simulation was nearly identical to actual EVA conditions. Cernan's experience laid the groundwork for using neutral buoyancy as an effective EVA training tool (Portree & Trevino, 1997).

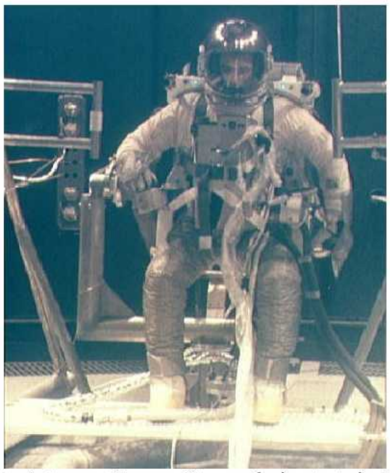

Figure 4. Astronaut Eugene Cernan during tests in Chamber B with AMU Photo from JSC Digital Image Collection, PHOTO ID S66-27376, taken 02-19-1966.

Figure 5. Astronaut Eugene Cernan during training with AMU on the KC-135 low gravity aircraft. Photo from JSC Digital Image Collection, PHOTO ID S66-31665, taken 05-03-1966.

During Gemini XI, crewmember Richard Gordon attempted to perform the U.S.'s first "complex" EVA with several planned tasks, including the relocation of the attachment of a 30m (100 ft) tether stowed on Agena 11 to Gemini XI's nose, the retrieval of an S9 nuclear emulsion scientific package, and the testing of a number of EVA tools including the "golden slipper" foot restraint, an HHMU, and a "torqueless" power tool. While relocating the tether attachment, Gordon found that the G4C spacesuit's internal pressure forced his legs together, preventing him from attaching the tether to the nose of Gemini. This experience was counter to his training aboard the zero-g aircraft, and this simple task that he had performed during short bursts of parabolic-flight induced microgravity took him 30 minutes to accomplish on orbit in a pressurized suit. Up until this point, neutral buoyancy training had not been viewed as necessary training for EVA task operations, and thus Gordon had spent little time training underwater despite the recommendation of his colleague. In space, however, Gordon had found it very difficult to work in the pressurized suit, and upon return he passionately encouraged Apollo surface astronauts to practice any and all required EVA tasks in pressurized, suited training events (Portree & Trevino, 1997).

Hence, before the next attempt of a "complex" EVA on Gemini XII, crewmember Edwin "Buzz" Aldrin conducted five neutral buoyancy training sessions in addition to the required microgravity EVA aircraft training. Aldrin also trained with the near immobility of the stiff G4C suit in the Thermal Vacuum chamber at NASA's MSC. It was this extensive training that enabled Aldrin to easily perform many of the tasks Gordon had attempted and several additional tasks, including cutting cable and fluid lines, fastening rings and hooks, and tightening bolts. In all, project Gemini missions involved nine EVAs for a total of 12 hours and 22 minutes of EVA experience.

The Gemini EVAs, although at times plagued with problems, demonstrated the feasibility of employing humans in free space to accomplish tasks (Newman, 2000). From these early EVAs came several key lessons:

1. Tasks were found to take longer on orbit than observed in training.
2. Umbilicals were useful for EVA.
3. Loose items must be tethered to prevent loss.
4. Body and foot restraints are important to maintain body position.
5. Underwater simulation training led to higher success rates on orbit.
6. Training in a pressurized suit was important for situational familiarization and increased strength and endurance.

Apollo EVAs (1967-1972)

Two primary objectives for the Apollo program were to land safely on the moon and to explore its surface through a series of increasingly complex EVAs. In all, six lunar surface missions were accomplished with 14 successful EVA sorties. Thus the EVA evolved from an experimental activity to a useful, functioning exploration mode. During Apollo EVAs, twelve crew members spent a total of 160 hours in spacesuits on the moon, covering 100 kilometers (60 miles) on foot and aboard the lunar rover, and ultimately collecting 2196 soil and rock samples (Newman, 2000).

Apollo EVAs differed from Gemini EVAs in four distinct ways. First, Lunar EVAs were remote from the host vehicle. This provided crewmembers a vast exploration area, but the added mobility introduced the requirement of a portable life support system, as the tethered umbilical was far too restrictive. It also required the EMU be capable of providing a warning of a pending consumable limitation and a subsequent plan of action to return to the vehicle. Second, the lunar EVA environment was significantly different than the microgravity milieu of Gemini. The Lunar surface is dusty, abrasive, and experiences a significantly varying temperature, all of which would play significantly into the design of the spacesuit. In addition, the reduced gravity (~1/6 g) would requires the crewmembers to bear a fraction of the EMU weight. Third, lunar exploration spacewalks involved walking instead of floating in microgravity, and thus were high-metabolic EVAs. Finally, the aggressive objectives of the Apollo program were unprecedented in complexity, requiring the development of new technologies, tools, and extensive 1-G training for the EV crew (Widle et al. 2002).

Due to these vast differences, NASA designed a comprehensive program for conducting lunar EVAs. Lunar surface astronauts studied geology and took field trips to sites on Earth thought to possess similar topography as the landing locations on the moon (e.g. Meteor Crater in Arizona). Also, a partial gravity simulator was developed by using an 81^{o} inclined surface on which lunar EVA teams would walk, utilizing a suspending harness to offload excess weight. The resultant force allowed crew to simulate the Moon's 1/6th gravity. KC-135 parabolic flight training was also completed for additional practice in a low gravity, lunar simulated environment.

Another training modality used to train lunar EVA crew was MSC's 5-acre outdoor "rock pile," where suited crewmembers practiced walking and collecting geological samples. During some training events, a truck-mortared, air-actuated weight support system termed "pogo" was employed to simulate lunar gravity levels. Later, Apollo crews practiced driving the lunar rover over the variety of simulated terrain found at the "rock pile."

Finally, neutral buoyancy training in JSC's Water Immersion Facility (WIF) was exploited for specific task training. These tasks inculded contingency clearing of the hatch and for egress and ingress of the lunar module (Wilde et al.2002).

As suggested by Eugene Cernan, a significant portion of EVA training that was developed during the Apollo program focused on the familiarization and use of tools in a pressurized glove. The selections of tools used for the specific tasks to be performed were chosen during the planning phase of each mission and specialized tools were developed when existing tools proved insufficient. Crewmembers trained tool manipulation in the 1-G environment as well as in the pressurized suit. Many of the tools used EVA can be found in a traditional toolbox; however, handholds and tethers present some unique features.

The first lunar surface EVA was accomplished by Neil Armstrong and Edwin "Buzz" Aldrin in the Southern Sea of Tranquility on July 20, 1969. Unlike previous EVAs, the first steps of a man on the moon were witnessed by approximately 600 million people watching the live television broadcasts. Crewmembers Armstrong and Aldrin collected rock and soil samples, planted a US flag, captured video imagery, and deployed EASEP (Early Apollo Surface Experiment Package). Similar to the spacewalkers before them, Armstrong and Aldrin found that even the best EVA training was no substitute for actual experience. The crew reported loping as the preferred method of movement, and that lunar dust quickly covered everything and was quite slippery. Armstrong later reported that the 1/6th partial-gravity training back on Earth was actually more strenuous than the 1/6 g-levels experienced on the lunar surface. Additionally, like many of the previous EVA experiences, surface activities took longer than expected.

A collection of lessons learned was gathered from eight of the surviving Apollo EVA crewmember by Conners et al. 1994 to influence the planning of future lunar EVA exploration. The results of the survey can be summarized as follows:

1. Integration of crew, equipment, and facilities should be viewed as a total system.

2. In subsystem design, simplicity and reliability are preferred over functionality.
3. In future EVA missions there should be a general movement toward increasingly greater crew autonomy. The on orbit crew should take a larger role in monitoring the EVAs by assuming primary responsibility forsome of the activities previously performed by flight controllers back in Mission Control.
4. Due to the length of future missions, the crew timeline should not be tightly scheduled.
5. A two man team, as used for Apollo missions, is the desired basic unit of exploration; however larger numbers may be appropriate in some cases.
6. Baseline EVAs should be 7-8 hours in duration; however, when and how many EVAs to be conducted (i.e. one day on one day off) should not be predetermined.
7. When considering suit design, the major driver should be suit flexibility and mobility; crewmembers suggested that the suit hug the body like a second skin.
    a. Crew placed significant emphasis on improved glove development
8. EVA preparation is necessary, but it should be concise and productive; combine events whenever possible.
9. Lunar dust is ubiquitous; keep EVA equipment separate from living quarters; use dust repelling equipment.
10. Install automation where appropriate (i.e. automatic suit check out).
11. Rovers are useful for translating with tools.
12. Equipment should be designed to fit the task, not vice versa.
13. When it comes to training, train the crew hard.
    a. The crew should train under realistic conditions (1/3 or 1/6 g) whenever possible.
    b. The crew should train to the mission, including contingencies; practice is important for performing under adverse conditions.
    c. Sustained mental performance is the toughest training issue, as well as interpersonal relations during lengthy missions.
    d. The crew should train with tools of the same weight and stiffness as would be used on the lunar or planetary surface.
    e. The crew should maintaining their own equipment during the training process.
    f. The crew should train in the pressurized suit and for an extended number of hours.
    g. The crew should train for the mission as an integrated whole and not just in segmented parts.

Skylab EVAs (1973-1974)

The Skylab program proved to be instrumental in demonstrating the power of extravehicular activity in manned spaceflight. Skylab was NASA's first space station. It was launched in 1973, six months after the last Apollo Moon landing. In order to have the functionality to replace one or all crew at a moment's notice, spaceflight training increased significantly for the Skylab (SL) astronauts. Required EVA training alone was increased to approximately 156 hours: 1-G events varied by crew (108 hours for SL (2), 127 hours SL (3), and 119 hours for SL (4)) as did the underwater training in the Neutral Buoyancy Simulator (NBS) (48 hours (SL 2), 57 hours for SL(3), and 42 hours for SL (4)) (Shayler, 2001[2]). The NBS at Marshall Space Flight Center (MSFC), in Huntsville, Alabama, was utilized to train specific EVA tasks, including the installation and removal of film magazines and the recovery of samples left outside for experimentation. The NBS was also used extensively to develop the complicated procedures for deploying SkyLab's solar sail and sun-shield, and it proved to be a valuable tool for developing and refining generic EVA techniques (Shayler, 2001 [2]). In addition to the NBS, low gravity parabolic flights were still used to train specific EVA techniques including microgravity maneuvers, tumble and spin recovery, and the specific EVA task of exchanging film magazines.

Extravehicular activity became significantly important to the Skylab program from the moment it launched. One minute after launch, SkyLab's micrometeoroid shields ripped away from its outer surface prematurely deploying six solar panels. This resulted in severe damage to one and complete loss of solar array 2 due to atmospheric drag. The power generated by the remaining panels was insufficient to keep thethe station functional, and to add to the concerns, the station began overheating due to the missing shield. The program hinged on the ability of the first three crewmembers to repair the damage. Astronaut Paul Weitz ventured out of Skylab on the first EVA in a modified, umbilical Apollo EMU to try and free the jammed solar array. Using the tools available on orbit, Weitz attempted to dislodge the jammed array while Kerwin attempted to stabilize him by holding his feet. To no avail, the crew became concerned that the task could not be accomplished with tools aboard.

A plan was quickly developed by EVA trainers on the ground and uplinked to the crew aboard Skylab. EV crewmembers Joesph P. Kerwin and Charles "Pete" Conrad fabricated tools from onboard materials and rehearsed the plan inside the module. Once outside, Kerwin found Skylab differed from the ground mock up he had trained on in the water tank in Huntsville. The foot restraints were not in the positions he had expected, and he was forced to hold on with one hand while attempting to position a "pole-like" cable cutting release tool with the other. During an EVA of 3:25, and using all their strength and their fabricated tools, Kerwin and Conrad successfully released the jammed solar array, providing much needed power to the damaged Skylab (Figure 6).

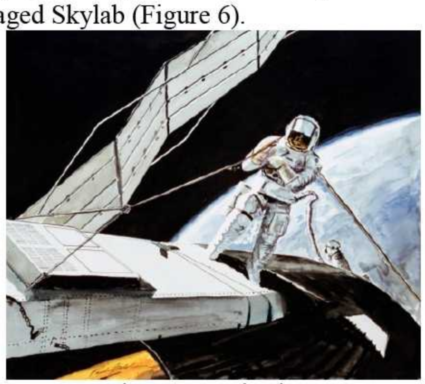

Figure 6. An Artist Concept showing Astronaut Charles Conrad Jr., Skylab II Commander, attempting to free the Solar Array System wing on the Orbital Workshop during Extravehicular Activity (EVA) at the Skylab 1 & 2 Space Station cluster in Earth orbit. The Astronaut in the background is Joseph P. Kerwin. JSC collection: S73-27508.jpg http://io.jsc.nasa.gov/app/info.cfm?pid=308350

The success of the Skylab EVAs convincingly demonstrated the need for EVA capability on manned spacecraft. Extravehicular activity literally saved the Skylab program. In addition, the Skylab highlighted that human presence in space offers many advantages to ensure mission success including flexibility and dexterous manipulation, human visual interpretation, cognitive ability, and real-time approaches to engineering problems. Skylab EVAs also demonstrated the importance of a manned space crew's ability to:

1. Be flexible and trained with a generic set of EVA skills.
2. Have multiple crewmembers who are EVA qualified.
3. Be able to think and innovate solutions when needed.
4. Have mockup and training modalities be as accurate as the flight hardware.

In all, Skylab astronauts logged 17.5 hours of planned EVA and 65 hours of unplanned EVA for the repair of the station.

Space Shuttle EVAs (1981- Present)

When Apollo XVIII and later missions were cancelled, the Space Shuttle was still in the concept phase. In 1969, NASA envisioned the shuttle as a reusable vehicle that would perform crew transfer, cargo delivery, and satellite deployment and capture. Initially, EVA was viewed only as an option in emergencies; however, as the program evolved, EVA emerged as a major component. As NASA's direction changed from launching expendable vehicles to using a reusable orbiter with solid rocket boosters, so did the direction of the EMU development. Engineers began designing a reusable, modular EMU with a stock of standard-sized parts that fit a wide range of crewmember anthropometrics.

From 1983 through 1985, 13 two-person EVAs were performed during the use of the Shuttle Transportation System (STS), or more commonly called Space Shuttle missions. The first shuttle EVA (and first EVA since February 1974) was a 4 hour and 10 min expedition to test the new STS (Shuttle Transportation System) EMU and EVA equipment during STS-6 on April 4, 1983 (Portree & Trevino, 1997). Astronauts Story Musgrave and Donald Peterson evaluated the STS EMU mobility by translating aft along the handholds inside the payload bay door hinge and assessed the contingency EVA procedures developed for shuttle (Figure 7). Since the first shuttle EVA, shuttle crewmembers have accomplished many tasks including demonstration of the Manned Maneuvering Unit (MMU), the Remote Manipulator System, and a specialized tool for the capture and berthing of satellites and other space structures.

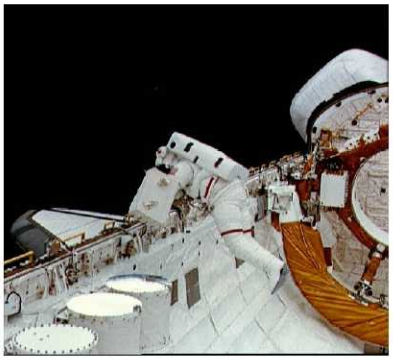

Figure 7. Story Musgrave translates down the Challenger's payload bay door hinge line with a bag of latch tools. http://images.jsc.nasa.gov/luceneweb/fullimage.jsp?photoId=S83-30212.

Many unique challenges are faced by EV crews during microgravity spacewalking missions in the EMU. These challenges include:

1. Reduced visibility due to changes in illumination, contrast, and field of view.
2. Reduced sense of orientation due to changes in vestibular stimulation.
3. Reduced range of motion due to limitation of the extravehicular mobility unit (EMU).
4. Compromised strength due to fatigue (most significantly hand fatigue), hardware design, and adaptation to weightlessness.

(Ricco et. al, 1997)

To combat and overcome these and other challenges faced during shuttle EVAs, the development of the EMU, EVA support tools (i.e., foot restraints, handholds, and specialized tools), and EVA training are credited with the reduction in Shuttle mission workloadNeuman, 2000), and specialized EVA training facilities have been developed and advanced to aid continued work efficiency.

Special EVA Training Facilities for Shuttle

Special EVA training facilities have evolved to help develop and nurture the skills required for EVA. An ideal EVA training facility is one that completely and accurately simulates all of the conditions that will be encountered during a mission including temperature, pressure, lighting, and microgravity (Thuot and Harbaugh, 1995). The microgravity milieu of low earth-orbit is difficult, if not impossible, to fully model in a 1-G environment. Textbooks, classes, and numerous specially designed facilities are utilized to replicate microgravity, and these training tools are used in concert to develop a specific skill set employed by shuttle and International Space Station (ISS) EVA crewmembers. In addition, present training facilities employ high-fidelity hardware mockups, worksites, and tool locations.

There are a number of major facilities, all housed at JSC, that are utilized during EVA training today. They include the Space Vehicles Mockup Facility (SVMF), the Sonny Carter Training Facility, the Neutral Buoyancy Laboratory (NBL), the Virtual Reality (VR) Laboratory, as well as vacuum chambers, a precision air bearing floor (PABF), and the DC-9 low gravity aircraft.

The SVMF consists of full scale mockups of the International Space Station, the Shuttle, and other trainers pertinent for spaceflight training. These modules are commonly high-fidelity from a visual standpoint, but are limited in their actual functionality. From an EVA task perspective, the SVMF is used to train EVA equipment transfer from shuttle to station post-docking, in preparation for the actual spacewalks, fluid quick disconnect operation for installation of critical equipment on orbit, repair of the Orbiter's thermal protection system (TPS), and other shuttle contingency tasks that require high fidelity training hardware. EVA skills are also taught at the SVMF, using the Partial Gravity Simulator (PGS, aka "POGO") and a precision air bearing floor (PABF). PGS (Figure 8) and PABF are employed to simulate zero-G and to accentuate the effects of Newton's Laws of Motion. Similar systems were originally developed and utilized during Apollo and Gemini training, and are still used for certain EVA skill applications today. In the PGS, a crewmember is suspended from an active pneumatic system that provides a vertical degree of weightlessness. The PGS also slides along a low-friction rail, giving a second degree of freedom in the horizontal direction. PGS is most often used to teach crewmembers how to stabilize themselves and react the forces generated by the tools they use, such as the technique for reacting the torque generated by the Pistol Grip Tool (PGT), a "cordless-drill" type tool designed to drive bolts.

Figure 8. EVA Task Instructor Sandra Moore suspended from PGS.

Neutral Buoyancy Lab (NBL)

As previously discussed, Neutral Buoyancy training dates back to the mid 1960's, after Eugene Cernan had difficulty executing EVA procedures on orbit despite completing the required low gravity training achieved with parabolic flight in the KC-135 aircraft. From that lesson learned, EVA instructors realized that astronauts needed longer than the 30 seconds of weightlessness achieved during each parabola to adequately train for EVAs, so they explored training EVA tasks underwater. It was quickly apparent that neutral buoyancy training reduced part task training, increased both integrated training and the overall training quality, and provided better timeline fidelity.

The Sonny Carter Neutral Buoyancy Laboratory, located at the NASA Johnson Space Center, has become the primary EVA training facility for EVA tasks and skills. Construction on the gigantic water immersion facility began in the mid 1990's. The NBL pool is 202 ft in length, 102 ft in width, 40ft in depth, and holds 6.2 million gallons of water. Since 1995, the laboratory has been employed for crew training and for EVA procedure and hardware development. The immensity of its size is essential; the vastness of the NBL allows an EVA crew to perform valuable end-to-end timelined runs, mimicking entire spacewalks. Task choreography can be revised repeatedly, so that when a crew finally performs the timeline for real on orbit, the spacewalk has been designed for maximum efficiency.

The NBL accommodates both full-sized Shuttle and ISS mockups, multiple control rooms, an environmental control system, a communication system, a water treatment system, closed circuit TV's, cranes and a specialized diving medical treatment facility (Figure 9). Figure 10 shows EVA Task instructor Matthew Gast developing an EVA timeline for STS-128/17A in the NBL.

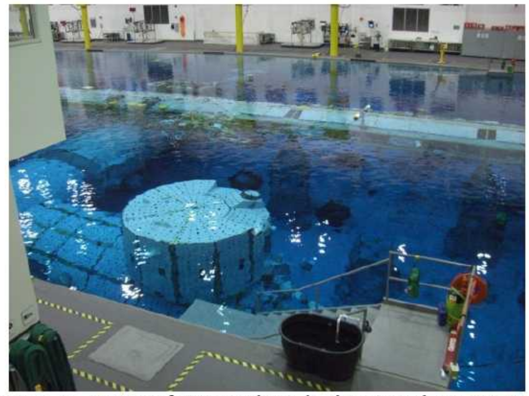

Figure 9. Image of ISS mockups in the Neutral Buoyancy Lab.

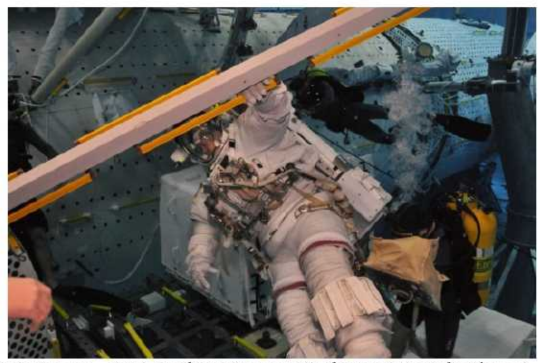

Figure 10. EVA Task Instructor Matthew Gast evaluating an upcoming EVA timeline for STS-128

Virtual EVA

Virtual reality (VR) technology allows crewmembers to interact with a computer-simulated exterior environment of the Space Shuttle and ISS. VR training aids for spacewalk preparation began in the 1990s. The NASA JSC VR laboratory possesses two VR stations consisting of a 3D display headset, EMU gloves, and an EMU Display and Control Module mockup. In this 3-D virtual world, the crew can translate anywhere on the shuttle or ISS by simplygrabbing from one handrail to the next, or be virtually translated via the station robotic arm (Space Station Remote Manipulator System or SSRMS). Figure 11 shows Astronauts John "Danny" Olivas and Christer Fuglesang training for EVAs on STS-128/17A in the VR lab.

In addition to the visual simulation of the space station, robotic arms, or shuttle, the VR helmet/glove combination can be employed with a robot named Charlotte to accurately simulate the zero-g mass handling characteristics of large orbital replacement units (ORUs). Olivas and

Fuglesang used Charlotte to train the removal and replacement of one of the largest ORU ever handled by EV crewmembers on orbit, the Ammonia Tank Assembly (~1850 lbs).

Finally, the VR facility is used to train EV crewmembers in the use and operation of the Simplified Aid For EVA Rescue (SAFER), a crewmember-controlled contingency system used for self-rescue, should the crewmember become disconnected from structure. The SAFER is a self-contained, gaseous nitrogen, propulsive backpack self-rescue system that provides an EV crewmember with self-rescue capability for any ISS-based EVA. This training involves separating a crewmember from structure in the virtual world, and then requires the crewmember to use the SAFER to conduct a self-rescue. Due to the limited quantity of gaseous nitrogent propellant, a crewmember must become proficient at self-rescue or risk exhausting SAFER propellant before returning to structure.

Figure 11. Astronauts Danny Olivas and Christer Fuglesand train for their upcoming EVAs on STS-128. Photo from JSC Digital Image Collection, PHOTO ID JSC2009e12083

Computer Based Training (CBT) and Imaging Software

In addition to training facilities, stand-alone computer based teaching programs and review modules have proven to be effective tools in training, and for review on long duration missions since the STS program. CD ROMs and other computer based training elements were found to be very beneficial to aid crews in re-planning mission objectives, reviewing EVA techniques that had not recently trained, and evaluating task-specific body positions. One of the most effective is Dynamic Onboard Ubiquitous Graphics (DOUG). DOUG is 3-D computer imaging package utilized by both the Robotics and EVA training teams to aid in planning and training spacewalks. Its package contains 3-D models for the ISS, Space Shuttle, and several EVA tools. Crewmembers often utilize DOUG onboard the shuttle and ISS during procedure review before an upcoming EVA, to visually walk through the translation paths and worksites.

Hubble Space Telescope Missions

One accolade of U.S.Space Shuttle EVAs are the Hubble Space Telescope (HST) missions. HST, deployed from the Space Shuttle in 1990, was designed for periodic servicing missions to enable maintenance, repair, and enhancement. Since its launch, there have been five highly successful HST EVA-intensive missions: STS-61 in December 1993, STS-82 in February 1997, STS-103 in December 1999, STS-109 in March 2002, and the last scheduled servicing mission, STS-125, in May 2009. EVA tasks on these missions ranged from changing out small data recorders to large telephone booth-sized new instruments. Successfully overcoming challenges ranging from re-planned activities tounscheduled contingencies, returning crews have creditedthe variety of training methods and the extensiveness of the training assome of the most essential elements of success.

HST EVA training flows have been, in general, more rigorous than the training flows for other shuttle missions. Additionally, tHST EVA flows had significantly higher NBL run to flight training ratios than current ISS EVAs.

Early HST missions were trained at MSFC in the Neutral Buoyancy Simulator (NBS) since MSFC managed the design and development of the telescope. The NBS itself was designed by the U.S. Army in 1955 at the Red Stone Arsenal to provide a zero-gravity simulator for research, testing, and development. The heart of the NBS is a 40ft deep, 75 ft diameter 5.3 million gallon, temperature controlled water tank. Figure 12 illustrates one of 32 separate training sessions conducted by four of the STS-61 crew members in June 1993. The HST mockup was separated into two pieces because the water tank depth could not support the entire structure in one piece. The three-week training process allowed mission trainers to refine the timelines for the five separate spacewalks conducted during the December 1993 flight.

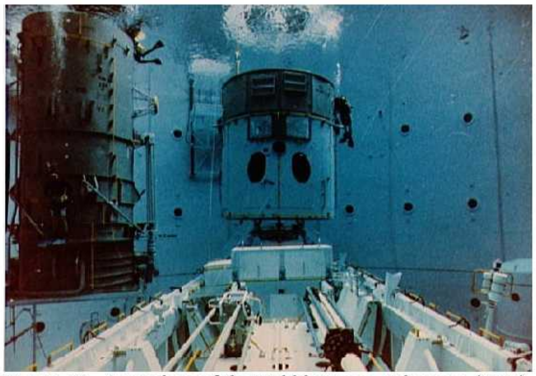

Figure 12. A mockup of the Hubble Space Telescope (HST) in the MSFC NBS for one of 32 separate training sessions conducted by four of the STS-61 crew members in June for the 1993 HST servicing mission. JSC collection: S9340315.jpg

Later HST missions were managed by Goddard Space Flight Center (GSFC), EVA training transpired both in the JSC NBL and on real flight hardware at GSFC. Not only were these EVA flows given significantly higher NBL run to flight training ratios than are currently used for ISS EVAs, but the HST crews were given more developmental NBL water runs as well. These additional water events were viewed as necessary, due to the sheer complexity of the assigned EVA tasks. STS-109 (HST SM3B) had a ratio of approximately 10:1 to 13:1 and earlier flights often had even more. Ironically, the last – and probably most complex – HST flight, STS-125, ranged only between 7:1 and 9:1, considerably less than previous HST missions. The difference can be attributed to a few factors, including NBL availability and new super high fidelity 1G trainers (Hansen, 2009). The PGS, aka POGO, modality was used along with the high fidelity HST 1-G trainers built by Goddard Space Flight Center to provide HST crew member with an accurate feel for inserting and removing hardware from the telescope. Hi-fi trainers were also built to overcome issues ranging from those encountered on previous missions to the sensitivity and difficulty of replacing hardware that was not originally designed or intended to be replaced by an EVA crewmember.

Philosophy on EVA Training: Shuttle Flight Specific Mission Training vs. Long Duration Flight Generic EVA Training (1998-present)

The philosophy of EVA task training shifted significantly with the ambition of the International Space Station (ISS) assembly and maintenance requirements. In addition to the majority of EVA tasks becoming more complex, the training programs have become more international, with crewmembers from countries across the world including America, Canada, Europe, Russia, and Japan requiring training. Special EVA cadres were formed within the astronaut core and programs were developed to select and qualify crewmembers for EVA. EVA cadres were then further divided into crew who would train for EVA shuttle flight-specific missions and those who would train as long duration ISS residents.

EVA task training is essential for success in both flight specific EVA missions and long duration flight. The training methodology, however, for these two types of flights, is quite different. As would be expected, preflight training places a strong focus on crewmember safety in both cases. For short duration missions, however, specific repetitive task choreography is essential, while long duration flights rely more heavily on basic skills, *in situ*, just in time, and proficiency training.

ASCAN EVA Task Training

The development of a generic skills set begins with the Astronaut candidate (ASCAN) EVA training flow. This flow was designed to familiarize crewmembers with the fundamentals of performing an EVA. ASCANs begin with hands-on classes covering EVA tools and the intricacies of the Extravehicular Mobility Unit (EMU) or space suit. Such classes introduce crewmembers to the nomenclature and constraints of approximately 68 of the primary tools, tethers, restraints, translation aids, and bags used during EVA in a t-shirt environment. An emphasis is placed on nomenclature, since communication between crewmembers and with the ground require clarity. The fundamental 1-G classes are followed by a set of four different water runs in the Neutral Buoyancy Lab (NBL). These runs are progressive (each builds upon the skills learned in the previous run), and are dedicated to introducing the ASCAN to operating the EMU in a neutrally buoyant environment, learning basic EVA skills, practicing fundamental EVA operations, and instilling good EVA habits such as situational awareness, verbalizing actions, optimal body position selection, and proper tether (life-line) protocol (EVA SOP, 2009).

Due to the sheer cost and preparation of EVA, it is necessary to have crewmembers develop and maintain physical conditioning that allows for the maximum EVA time possible. On orbit EVA tasks demand high levels of muscular exertion, stamina, physical and mental endurance, and psychomotor skills such as hand-eye coordination. The attributes that best suit an EVA crew member are those possessed by a "young, energetic, vigorous, well-conditioned athlete" (Abeles & Schaefer, 1986). Hence, in developing an EVA skills set, EVA training focuses on the manipulation of mechanical objects in a simulated EVA environment and an intensive physical conditioning program. The objective of the EVA instructor is to provide a rich and varied framework from which the student can research and determine his or her own preferred method for efficiently performing EVA tasks.

EVA Task Skills Program

If adequate achievement and aptitude is demonstrated in ASCAN EVA training, astronauts become eligible for the EVA Skills Program. This is a more thorough and rigorous series of training runs that work to improve the astronaut's ability to operate effectively and efficiently in the EMU. The program consists of a series of 1-G "table-top" discussion sessions, a number of SCUBA sessions to become acquainted firsthand with the translation paths and worksites, and up to ten NBL water suited events. Early Skills runs focus on basic EVA training and mission timeline development. These early runs allow crewmembers to discover and improve areas of weakness, and learn the nuances of developing a spacewalk. As training progresses, the tasks become more difficult and EVA instructors demand a greater contribution from the crewmember (EVA SOP, 2009).

To ensure the crewmembers become more involved as the training progresses, each of these later runs begins by providing the EVA crewmember with a set of tasks that need to be accomplished for either ISS maintenance or imminent ISS repair along with a set of constraints. To evaluate the EVA student's situational awareness, the crewmember is asked to develop a timeline and provide a list of tools and tethers needed to accomplish the tasks required. Students are provided a 1-G class with the evaluating EVA instructor, to discuss concerns, constraints, and to become familiar with hardware and mockups. Many students also SCUBA their timelines to examine the worksite, evaluate proposed body positions, and assess the developed plan.

Upon the completion of each NBL run, the EVA instructor conducts a debrief with the crewmembers, to identify and discuss areas of improvement. Instructor astronauts (IA), a group of experienced EVA crewmembers, also work to coach and evaluate EVA Skills students, and during each NBL water run and debrief, an IA is present to critique and provide insight and advice.

Upon successful completion of the Skills program, qualified astronauts are then eligible for a flight assignment as an EVA crewmember.

Flight Specific EVA Training

Once an astronaut is assigned to a shuttle mission, he or she follows a flight specific training plan developed by an EVA instructor who also works as the mission's spacewalk designer. This EVA instructor works closely with assigned crew to foster a timeline that works effectively for the individual crewmember performing each specific task, while incorporating requirements from the entire EVA community (safety, engineering, EVA tools etc.). For example, if the task involves removing and replacing an on-orbit battery, the instructor and the crewmembers will together evaluate translation paths, body position, tool stowage, and battery removal steps for the specific battery being replaced. Hence, the amount of training required for each EVA varies. NBL water runs nominally range from 4:1 to 7:1 depending on the "complexity of the EVA, prior crew experience, number of EVAs in a mission, and the interactions with other disciplines" (EVA SOP, 2009). The instructors and crewmembers may also SCUBA dive to develop preliminary timelines and examine translation pathways, body positions, and techniques. SCUBA provides access to shuttle and ISS mockups without being encumbered by the EMU, while minimizing the cost of developing an EVA. In most cases, initial EVA plans evolve through crew training and are flight-ready within 12 to 16 months. On orbit, EVA instructors provide the EVA crewmembers with real-time technical insight and guidance and respond to crew questions on EVA-related issues that unexpectedly arise.

In addition to flight specific tasks, EVA crewmembers are also trained for any number of specific contingency EVA scenarios that could arise on shuttle or station during that particular flight. Such tasks depend heavily on the payload setup in the shuttle payload bay and, if docking with ISS, the configuration of the space station before launch. Many of these tasks are heavily trained during the ASCAN and Skills flows and are typically only reviewed once or twice during flight specific NBL training events.

As the station grew in size and complexity, it became virtually impossible for astronauts to train for every possible maintainence and contingency EVA. Hence, the philosophy of EVA training for long duration crew members required a different training approach.

ISS Increment Crew EVA Training

Once an EVA-qualified astronaut is assigned a prime crewmember to a long duration ISS Increment mission, he or she follows a generic ISS Increment EVA flow. Developed by the EVA TASK and safety community, this flow ensures an EVA crewmember is prepared for on orbit operations. The generic increment flow begins with a review of the critical information EVA crewmembers first encountered during ASCAN training. The flow continues with three NBL maintenance pool runs and at least one SCUBA session to ensure the crewmember is familiar with 14 of the critical orbital replacement units (ORUs) that might need to be removed and replaced (R&R) during their long term stay on station and a generic set of task required to be mastered by all EVA crewmembers. During the ISS increment flow each crewmember is evaluated by EVA instructors, instructor astronauts, EVA safety, engineering, and the tools community in an EVAAT (EVA Assessment Team) run. The EVAAT run is a mock stage EVA run in the NBL. Procedures are provided to the crew in a fashion similar to how they would be uplinked to the ISS EVA crew aboard the ISS during a long duration mission. The EVAAT run provides the mission training team with a comprehensive evaluation of the crewmember's current EVA aptitude and identifies any deficiencies. By their nature, EVAAT runs develop and maintain an EVA standard of practice.

Training for Future Space Walks: Synergy of Past and Future Training Programs

Over the past 40 years, microgravity EVAs have been marvelously demonstrated, the techniques have been advanced and the complexity has grown exponentially, culminating in an orbital laboratory where NASA and international space agency partners can perform research in an attempt to improve our ability to explore the universe. But astronauts have not stepped foot on the lunar surface or performed a surface EVA since December of 1972. As manned spaceflight plans to return to the moon to establish a lunar base in preparation for Martian exploration, EVA training must evolve to meet these challenges.

Successful EVAs are a testament to the adaptability and skill of the EVA crew. The Gemini and Apollo programs established early that adequate EVA task training in flight-like modalities is necessary for success. Skylab EVAs demonstrated that adequate skills training and real-time approaches to engineering problems can lead to success even under adverse conditions. A conservative estimate from Shuttle flight-specific EVAs indicates that there are "at least ten hours of flight-specific ground-based EVA training for every hour of on-orbit [complex] EVA performed" (Ricco et. al, 1997). This training does not include estimates for contingency training. Significant advancements have also been made in training programs to facilitate long-term space station EVA. The fundamental nature of planetary EVAs will require a similar effort.

Early spacewalks and planetary base construction will most likely demand high levels of choreography similar to that of a flight specific mission to construct the ISS or repair HST. Although some tasks, like the constant tethering of hardware and tools, becomes less critical due to the presence of a gravity field, other potentially more difficult issues arise. EVA task training must evolve to account for these differences. Probably the most challenging difference is that the crew must learn to bear a fraction of the weight of the EMU they will be wearing and the hardware they will be manipulating. Pressurized EMU characteristics will also play a significant role in determining overall mobility of both locomotion and hand dexterity. Monitoring and controlling metabolic rate to maximize EVA time will be essential for EVA optimization. Specialized tools will need to be designed or modified, including robotic equipment, which may be necessary to aid in construction.

One of the critical EVA task training modalities for planetary EVAs is the development of an accurate partial gravity simulator. In the past, as documented earlier, much of the training has been accomplished with three primary techniques, including underwater immersion, low gravity aircraft flying Keplerian trajectories, and suspension systems. Parabolic flight is the only way to achieve *true* microgravity here on earth; however it is cost prohibitive on a grand scale, and only provides at most 30 seconds of partial gravity. A cable suspension method typically employs vertical cables to suspend a suited subject, relieving a portion of the weight exerted by the subject on the ground, thus simulating partial gravity. Suspension systems are the most economical partial gravity simulation technique, but limit the degrees of freedom for movement. Water immersion offers a suited crewmember unlimited duration and freedom of movement, but hydrodynamic drag dampens movement and buoyancy issues can interfere with flight-like training (Newman & Barratt, 1997). Research is underway at several universities to develop an accurate lunar gravity simulator to prepare lunar surface astronauts for surface EVAs. If possible, evaluation by lunar astronauts would be beneficial in the early stages of modality assessment and selection; as was seen during Apollo, techniques developed on the ground for something as simple as walking immediately evolved to a loping bound by crewmembers once on the surface of the moon.

Lunar dust is another significant issue that will arise during early EVA missions. Apollo crews reported that lunar dust quickly covered everything and was quite slippery. This may have significant impacts on tool operation and crew footing. In addition, orbital replacement mechanisms must be designed to protect and handle its inexhaustible presence.

Apollo crewmembers acknowledged the importance of understanding lunar geography and geophysics. Textbooks and applied Geology instruction are critical to studying the planetary surface and recognizing new findings. Analog sites here on Earth have been and will continue to be critical in developing, testing, and training for surface EVAs. These can be either created to be representative of a particular site or naturally occurring on the Earth's surface with representative characteristics (Hoffman, 2004). Of those sites constructed during the Apollo era only the site at USGS at Cinder Lake, Arizona still exists. This site has been utilized most recently for the Desert Rats program where the next generation of lunar and Martian experimental hardware/software and mission operational techniques are being evaluated by a group of NASA scientists and engineers as part of the new Constellation program. Figure 13 shows Astronaut Eugene A. Cernan (left), commander, and Scientist-Astronaut Harrison H. Schmitt, lunar module pilot, collecting lunar samples during EVA training at the Kennedy Space Center (KSC). Figure 14 is an image of experimental hardware from a Desert Rats excursion in Arizona.

Figure 13. Apollo 17 crewmen during EVA training. Photo from JSC Digital Image Collection, PHOTO ID S72-48888 taken 09-13-1972.

Figure 14. Image from a Desert Rats trial in the desert of Arizona.

Thurot and Harbaugh (1995) describe the ideal EVA task training facility as one that completely and accurately simulates all the conditions that will be encountered during a mission. Due to the complexities of planetary EVAs, creating just one EVA training modality to completely mimic all nuances would be impossible. From the successful construction of the International Space Station, current EVA crews have demonstrated that multiple modalities are adequate for training; however it is significantly important that when the modalities overlap, they are identical. In addition, it is vital that crews understand the ways in which each training facility is flight-like and the ways in which it is deficient.

Once the lunar base is constructed and manned, much more autonomy must be granted to the crew. Apollo crews recommended that there should be a general movement toward increasingly greater crew autonomy. Hardware and software must be developed to allow the in-situ crewmembers to take a larger role in monitoring and modifying each EVA's parameters, both with respect to EMU hardware parameters and the re-planning of tasks. This movement should be carefully planned and designed with highly experienced NASA EVA MOD flight instructors/controllers. These individuals have great insight into what level of autonomy could be achieved without putting the crew in danger (Hansen, 2009).

Training for these later missions should focus on an evolving skills set, much like long duration crew are trained today for ISS increments. Most importantly, crew must be able to demonstrate the ability to be flexible, innovative, and responsive to real-time changes that must be handled autonomously. This critical skill is not an easy concept to train or to develop. Research should be conducted to investigate the most efficient and effective methods for developing this skill in long duration crew. This skill is a combination of psychology, innovative thinking, and perseverance. Overlapping missions by a few weeks may provide on-coming crews with mentor/protégé on orbit experience that could never be replicated here on Earth.

Conclusion

EVA is now an established method for meeting human space mission objectives ranging from planned routine tasks to unexpected, untrained contingencies. Significant lessons learned from past NASA EVA programs have been collected, evaluated, and incorporated to help EVA training curriculum evolve into a program that will be successful for future exploration endeavors. The successful design of future planetary spacewalks depends on providing crew with the necessary skills set that will allow them to react appropriately in both expected and unexpected circumstances.

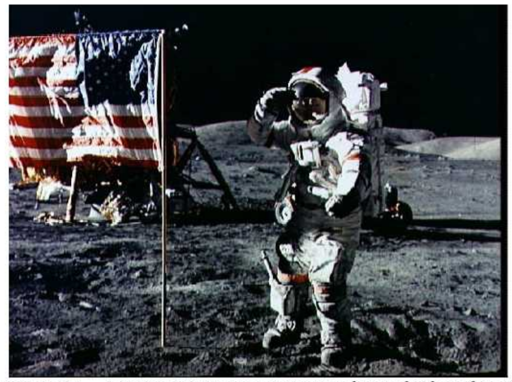

Figure 15. Astronaut Eugene Cernan salutes deployed U.S. flag on lunar surface. Photo from JSC Digital Image Collection, PHOTO ID AS17-134-20380, taken 12-13-1972.

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